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Research for Hybridization Degree and Logic Threshold Control Strategy of the Hybrid Power Gas Engine Heat Pump

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Abstract

Gas engine heat pump is the important distributed power supply system in the energy structure. Hybrid power technique plays an important role to improve the engine performance and the gas conversion efficiency of gas engine heat pump (GEHP). In this paper, the section of power hybrid approach is established and the relation of hybridization degree and gas consumption rate is analyzed. The results show that the optimum hybridization degree is 0.412; the rate power of motor is 8.75kW. The transmission ratio and the motor charging torque is 3 and 10Nm in the Mode C condition; the transmission ratio and the motor torque is 2 and 0Nm in the Mode D condition; the transmission ratio and the discharging torque of motor L is 1.5 and 10.5Nm. For a comprehensive, the logic threshold control strategy is useful to improve the gas conversion efficiency. Compared with GEHP system, the gas conversion efficiency can increases about 7.6% when the logic threshold control strategy is applied in the HPGHP system.

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Keywords: Hybrid power, GEHP; Parallel typ; Hybridization degree; Control strategy

1. Introduction

Gas engine heat pump is the important distributed power supply system in the energy structure due to its energy saving achieved by using a high performance natural gas engine [1-3]. At present, the fuel engine mainly work on

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part load in the GHP system and the operation condition is changing with external load. As a result, the operating condition of the gas engine often deviated from the nominal working condition, which leads to the reduction of average thermal efficiency and the increasing of heat loss of the engine [4]. The hybrid power technology has been proposed to improve the engine performance. The hybrid power gas engine heat pump (HPGHP) is a novel system combined with GEHP and hybrid power technique [5]. The novel hybrid-power gas engine-driven heat pump system, which mainly consumed the natural gas and was supplemented by the battery bank functioned as second driving energy source could keep the gas engine running in the economic zone as far as possible, and improve the total performance of the novel heat pump system [6]. And the hybrid power drive system can be divided into two main types: series-type and parallel-type [7, 8].

The optimal drive type and the power hybrid approach can improve engine performance and gas conversion efficiency. However, few studies have been made on it. Nowadays, a parallel-type drive system is proposed to analysis the operation performance, optimization matching and control strategy of the HPGHP system [9, 10]. In order to establish the design method of the HPGHP drive system, the difference between series-type and parallel-type has been studied in this paper. The design method is determined by gas loss coefficient. In addition, the effect of power hybrid approach on the gas consumption rate is analyzed. Meanwhile, the optimum hybridization degree can be obtained based on this analysis.

For a comprehensive, in-depth understanding of operating characteristics of the HPGHP, establish a suitable logic threshold control strategy of the HPGHP system is necessary. At present, the research on control strategy of hybrid drive system can be divided into four categories: logic threshold control strategy, the instantaneous optimal control strategy and control strategy based on fuzzy control, the global optimization control strategy [11]. Logic threshold control strategy, combined with optimal curve control strategy of the gas engine, straighten out the operating point of the lowest gas engine fuel consumption when running under a certain speed or under certain load through studying the characteristic curve of the gas engine [12,13]. This article mainly discusses the logic threshold, which composed of switching law of transmission and the motor torque control.

2. Selection of power hybrid approach

The drive system of HPGHP can be divided into two kinds of types: series-type and parallel-type. For series-type drive system, the output power of gas engine is all used to generate electricity and be stored in the batteries; for parallel-type drive system, the heat pump system is driven by engine and motor together. It has been proved that the parallel-type drive system is suitable for the GEHP system because it can improve the gas conversion efficiency [9]. For the parallel-type drive system, hybridization degree is used to describe the power hybrid approach [14]. It can be defined by the following equation,

$$R = P_m / (P_m + P_e) \tag{1}$$

2.1. Effect of hybridization degree on the economic zone

For the parallel-type system, the hybridization degree determines the economic operation zone of the gas engine, which means the equivalent level of gas conversion efficiency. The motor power can be calculated as 12.5R/ (1-R) by equation 1, which means that the range of the motor power is from 0 to 12.5R/ (1-R) and the range of gas engine output power is from 12.5R/ (1-R) to (12.5-25R)/(1-R). According to the definition of load rate σ, the relation between hybridization degree R and economic zone of engine is shown in the Table 1.

Table 1. The relation between hybridization degree and economic zone.

Hybridization degree R	Economic zone(the range of load rate)
0	0~1
0.091	0.1~0.9
0.167	0.2~0.8

0.231	0.3~0.8
0.286	0.4~0.8
0.333	0.5~0.8
0.375	0.6~0.8
0.412	0.7~0.8
0.444	0.8

2.2. Optimization solution of the hybridization degree

According to the relation between hybridization degree and economic zone, the relation between hybridization degree and the equivalent gas consumption rate can be obtained. In this paper, this relation curve is simulated by the Cubic Spline Interpolation. And the conversion equation between gas consumption rate be and the equivalent gas conversion efficiency ηp is as follows. The heating value of gas is 46.2MJ/kg.

$$be = 3600 / 46.2 / \eta_p \tag{2}$$

Fig. 1 shows the relation of hybridization degree and gas consumption rate. Firstly, the hybridization degree has little impact on the gas consumption rate when R<0.15. Secondly, the gas consumption rate increases with the increasing of hybridization degree, and then decreases when0.15<R<0.412. Finally, the gas consumption rate decreases with the increasing of hybridization degree, and then increases when0.26<R<0.444. It is concluded that the optimum hybridization degree is 0.412; the rate power of motor is 8.75kW.

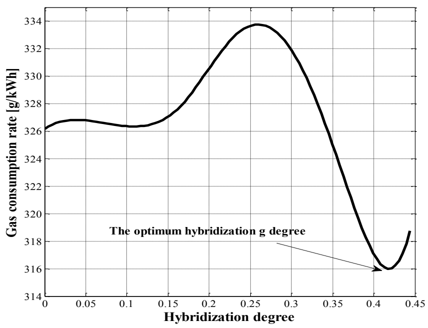


Fig. 1. The relation between gas consumption rate and hybridization degree.

3. Logic threshold control strategy

3.1. Description of HPGHP system

According to the design method of the drive system and power hybrid approach in section 2, the HPGHP system can be built and test bed and the schematic diagram can be established, which were showed in Fig. 2(a) and Fig. 2(b). The HPGHP system has several parts: the drive system, the heat pump system and waste heat recovery system. In the heating condition, the heat quantity is from indoor heat exchanger, jacket water and exhaust gas. In addition, the engine and motor is connected with one shaft, which makes the engine and motor can be kept the same speed all the time.

According to the experimental research of heat pump, the relation between speed and torque of compressor can be obtained as the Fig. 3 shows. The experimental test of heat pump is affected by the environmental temperature. In order to analyze the control law of drive system, the simulation curve is used to describe the numerical relation between the compressor speed and torque. The compressor torque increases with the increasing compressor speed.

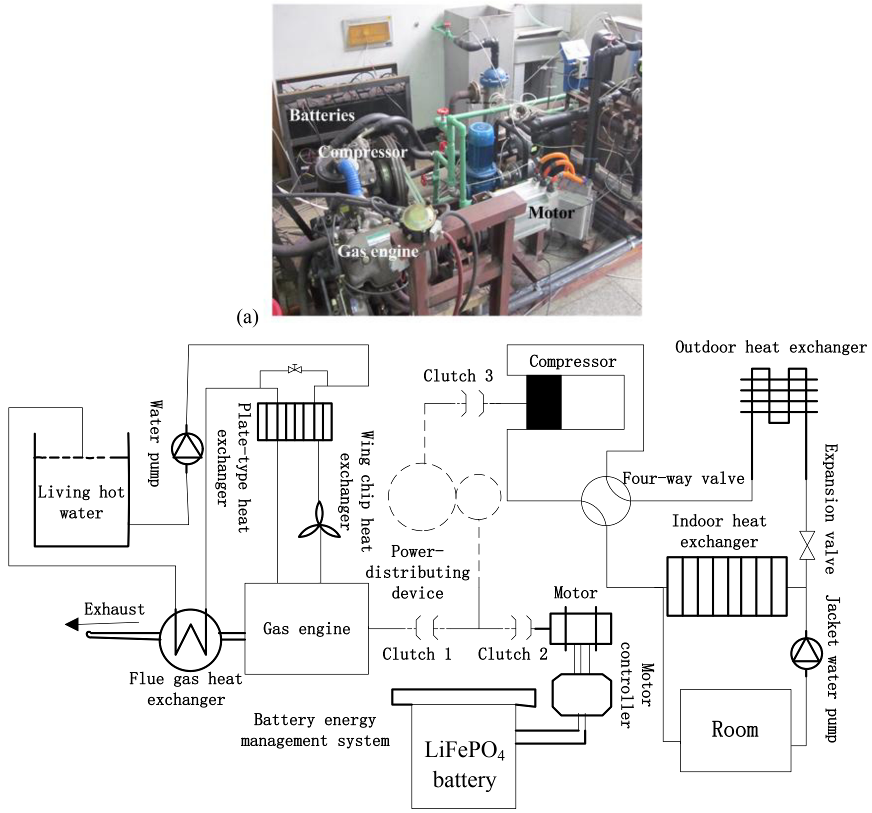


Fig. 2. Description of HPGHP system in the heating condition: (a) Test bed of HPGHP system; (b) Schematic diagram of HPGHP system.

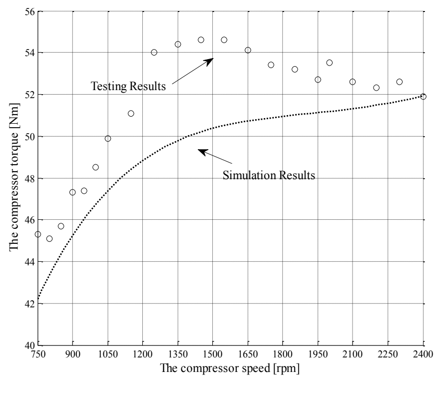


Fig. 3. The relation between speed and torque of compressor.

3.3. Switching law of transmission

For the parallel-type hybrid power gas engine heat pump, the control strategy is composed of transmission and motor, and it can be achieved by switch of transmission and the motor torque control. Be (Ne, Te) is the gas consumption rate of engine, which is the boundary parameter of the economic zone. The equation of Be (Ne, Te) can be achieved through the following expression, which is simulated by the gas engine test data [15].

$$be = 3429.5 - 2.012N_e + 192.4075T_e + 5.1972\times10^{-7} N_e^2 - 0.0039N_eT_e + 3.4593T_e^2 \quad (3)$$

The control object of logic threshold control strategy in this paper is gas engine. The object function is calculated by the following equations.

$$be(N_e, T_e) < 330g/kWh \quad (4)$$

Fig. 4 shows the operation boundary of gas engine, which indicates that the gas engine speed should be maintained between 2100 and 3800rpm. According to speed matching law between gas engine and compressor, the switching law of transmission can be obtained. When the compressor speed ranges from 700 to 1150rpm, the transmission ratio is 3 (Mode C condition); when the compressor speed ranges from 1150 to 1850rpm, the transmission ratio is 2(Mode D condition); when the compressor speed ranges from 1850 to 2400rpm, the transmission ration is 1.5 (Mode L condition). As a result, multistage gear transmission ratios in different speed ranges can make gas engine speed be maintained between 2100 and 3600rpm. So the switching law of transmission can be applied.

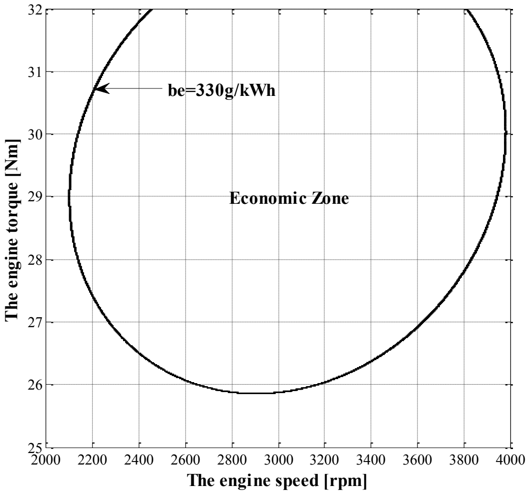


Fig. 4. The operation boundary of gas engine.

3.4. Control strategy of motor torque

The control object of motor torque is to keep gas consumption ratio of gas engine be less than 330g/kWh. According to the operation boundary of gas engine, the torque range of engine in different gas engine speed can be calculated as equation 5 shows.

$$[T_{low} \ \ T_{high}] = f(N_d) \quad (5)$$

The demand speed Nd and torque Td of parallel-type drive system can be calculated by the compressor speed and torque. As equation 6 shows, the value of transmission efficiency ηT is 0.98; the value of the compressor mechanical efficiency is 0.87; r is transmission ratio.

$$\begin{cases} N_d T_d \eta_T = N_c T_c / \eta_c \\ N_d = N_c r \end{cases} \tag{6}$$

In Mode L condition, the engine and motor drive the compressor together. The whole parallel-type drive system can meet the power balance as the equation 7 shows,

$$N_d T_d = N_e T_e + \eta_{em} N_m T_m \tag{7}$$

Where ηem is transmission efficiency between motor and engine, which is 0.98 in this paper.

In Mode C condition, the motor is used as generator. The whole parallel-type drive system can meet the power balance as the equation 18 shows.

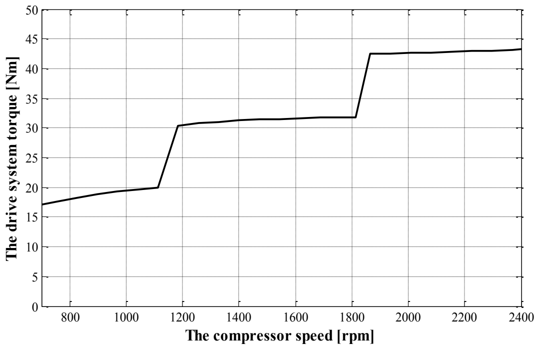
$$N_e T_e = N_d T_d + N_m T_m / \eta_{em} \tag{8}$$

In Mode D condition, the motor is not working; the motor torque is 0Nm. The whole drive system can meet the power balance as equation 19 shows.

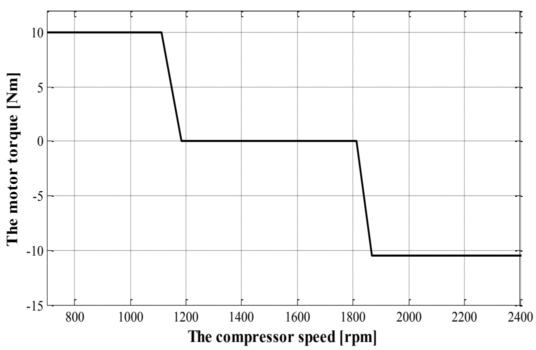
$$N_e T_e = N_d T_d \tag{9}$$

As the Fig. 5(a) shows, the demand torque of compressor increases with the increasing compressor speed from 17 to 20Nm in the Mode C condition; the demand torque of compressor is maintained at about 31Nm in the Mode D condition; the demand torque of compressor is maintained at about 42.5Nm in the Mode L condition.

According to the variation law of hybrid power system, the constant torque control strategy can be adopted to control the motor. As Fig. 5(b) shows, the charging torque of motor is 10Nm when the compressor speed ranges from 700 to 1150rpm; the discharging torque of motor is 10.5Nm when the compressor speed ranges from 1850~2400rpm; the motor is not working when the compressor speed ranges from 1150 to 1850rpm.



(a)



(b)

Fig. 5. Relation between torque and the compressor speed: (a) Demand torque of drive system; (b) Charging-discharging torque control strategy of motor

4. Experimental verification

In this paper, the experiment test is based on the HPGHP test bed which is built by the air conditioning and refrigeration laboratory from Southeast University Lab [9]. As the Fig. 6 shows, the gas consumption rate of gas engine can be controlled below 330g/kWh. In addition, the switching of transmission can also be applied in the GEHP system. The comparison between GEHP and HPGHP system can be studied by the experimental test in one operation cycle. The operation cycle is set to be one hour and the compressor speed ranges from 800 to 2400rpm in one cycle, as Fig. 7 shows.

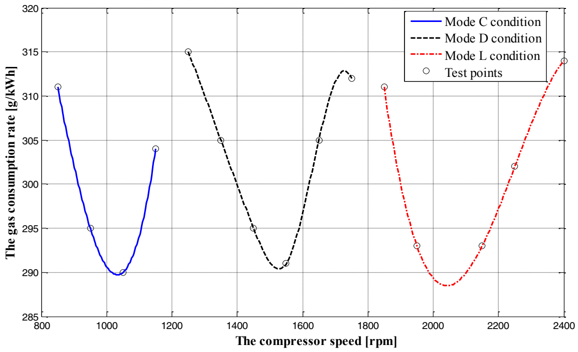


Fig. 6. The relation between gas consumption rate and compressor.

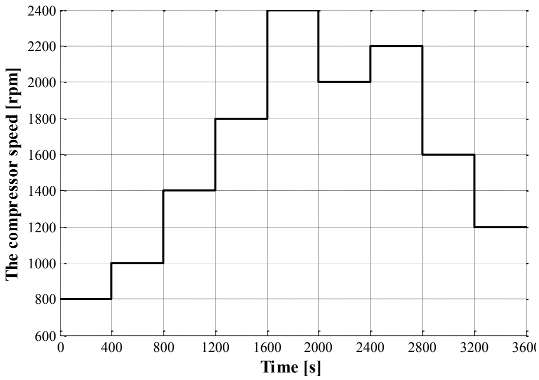


Fig. 7. The demand speed of compressor in one cycle.

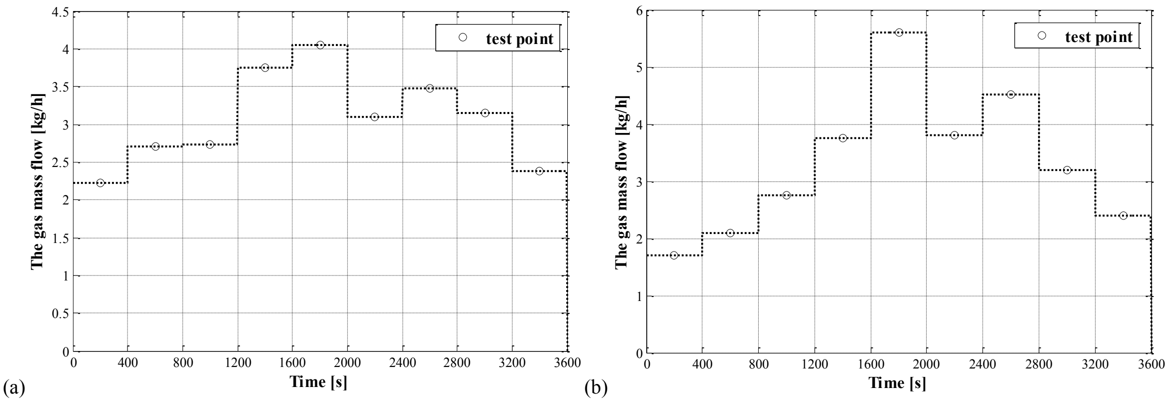


Fig. 8. The test point of gas mass flow of HPGHP system in one cycle: (a) HPGHP system; (b) GEHP system.

For the HPGHP system, the compressor speed is adjusted by the engine speed and the transmission ratio. And for the GEHP system, the compressor speed is determined by the engine speed. The gas mass flow m can be obtained in different operation condition. As Fig. 8(a) and Fig. 8(b) shows, the gas mass flow changes with the compressor speed.

The gas consumption M can be calculated by the equation 10.

$$M = \frac{1}{3600}\int_0^1 m\,dt \tag{10}$$

The results show that the gas consumption of HPGHP system is 3.06kg in one cycle; the gas consumption of GEHP system is 3.31kg.

5. Conclusions

In this paper, the section of power hybrid approach can be established as well as the relation between hybridization degree and the equivalent gas consumption rate can be obtained. The optimum hybridization degree is 0.412. The rate power of motor is 8.75kW.

In the second part of the research, the logic threshold control strategy is proved to work. It is composed of switching law of transmission and constant torque control of motor. The results show that the transmission ratio and the motor charging torque is 3 and 10Nm in the Mode C condition; the transmission ratio and the motor torque is 2 and 0Nm in the Mode D condition; the transmission ratio and the discharging torque of motor is 1.5 and 10.5Nm.

Compared with GEHP system, the gas conversion efficiency can increases about 7.6% when the logic threshold control strategy is applied in the HPGHP system.

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